Progress on a Small Multi-Cycling Cryogenic Fluid Flow Valve

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Abstract

Mission Research Corporation (MRC) in cooperation with the Jet Propulsion Laboratory (JPL) has developed a new small remote-controlled fluid valve. The motivation for developing this valve came from the requirements of a future International Space Station experiment called MISTE (Microgravity Scaling Theory Experiment). This experiment requires an *in-situ*, low temperature operated, fluid valve that can be open/closed over 50 times during a 4.5 month flight. The successful operation of MISTE and other space-based and ground-based laboratory experiments now in development will require reliable cryogenic fluid valves that are remotely operated, helium leak tight, non-magnetic, very low power, and which have a small dead volume. The new valve is normally closed and requires fluid actuation at a pressure of approximately 600 kPa to open. The heart of the valve design is found in the configuration of the valve seat and sealing poppet. The design of these two surfaces was derived from work performed previously during a five year development program for a larger MRC remote-controlled, cryogenic fluid flow control valve. More than 50 of the larger valves have been produced and delivered for space flight applications. The new small valve has only three moving parts, which move less than 0.012 cm when the valve fully opens or closes. The bearing surfaces in the valve operating mechanism are all flexure (except for the valve poppet) and thus the valve is expected to have a lifetime of thousands of open/close cycles. The materials and processes used to fabricate the new valve have been flight certified. Results from the first extensively tested prototype show repeatable behavior with a leak rate of typically 3×10^{-8} scc/s after the first open/close cycle at 4.2 K, rising to about 10^{-6} scc/s after 100 cycles. Further tests and minor modifications are expected to improve the performance.

Keywords: space cryogenics; cryogenic valves; MISTE

Background

Reliable cryogenic valves have always been a problem for scientists performing low temperature experiments with liquid helium. Space flight qualified valves, which have the additional requirements of surviving launch vibration and of being reliable enough for expensive space missions, are even more of a problem. Valves for cryogen management in space dewars have been developed [1,2], including a commercially available valve made by Mission Research Corporation (MRC), however these valves are generally too large for typical low temperature experiments. A small cryogenic valve [3] was developed by Ball Aerospace and Technology Corporation (BATC) for the Lambda-Point Experiment (LPE) in 1992 [4]. This valve was re-flown during the Confined Helium Experiment (CHeX) in 1997 [5]. The LPE/CHeX valve, which was produced after an expensive development effort, was not required to open during orbital operations, and the number of open-close cycles only needed to support the integration and test of the experiment on the ground.

Experimental Requirements

The Microgravity Scaling Theory Experiment (MISTE) [6], which will be performed on the International Space Station within the Low-Temperature Microgravity Physics Facility (LTMPF) [7], will make an extensive study of several thermodynamic properties of ^{3}He near its liquid-gas critical point at 3.3 K. MISTE plans to measure constant-volume specific heat at several different densities at and near the critical density. In addition, MISTE will use the same sample cell to measure isothermal susceptibility in the near-critical region. These measurements will provide a large, internally consistent data set for comparison with renormalization-group theory and equation-of-state expressions. To perform all these measurements, the apparatus must be capable of changing the amount of fluid within the sample cell by opening and closing a low-temperature valve during on-orbit operation. Additional requirements on the valve for MISTE use is a small dead volume and low power dissipation. Because MISTE uses squid-based high-resolution magnetic thermometers, the valve must also be non-magnetic. A normally closed valve will allow the MISTE sample cell to be pre-filled to near the critical density before launch. The risk in the valve development is reduced for MISTE since ^{3}He critical point studies do not require a superfluid-tight valve. The MISTE leak rate requirement, $< 10^{-6}$ std-cm^3/s (scc/s) after 25 cycles, is based on the need for the average density in the sample cell to be sufficiently stable over time.

The MISTE experiment team decided that the legacy of extensive testing and refinement on the large commercial MRC valve [1] would be very beneficial to the development of a smaller valve for use in the experiment. MRC produced a prototype miniature valve which was evaluated at low temperature by the MISTE team.

Legacy

The design of the valve stem tip and seat are based on the stem tip and seat used in MRC's space qualified, motor operated, ½″ Cryogenic Valve (MCV). The MCV was originally developed in 1989 for a NASA Shuttle cryogen transfer demonstration project (SHOOT) [8,1]. Since that time MRC has delivered more than 60 valves mostly for space flight programs such as Gravity Probe B, XRS, ASTRO –E, and –F. Use of the MCV is also planned for the LTMPF dewar that will house the MISTE experiment.

Functional Description

Figure 1 is a schematic of the MRC mini-valve prototype. The valve configuration is normally closed. The valve sealing force is applied by way of a spring, which applies a given force to the end of the valve stem. The valve is actuated by a bellows arrangement, which applies a counter force when gas pressure is applied to the actuator inlet. The effective valve orifice diameter is equal to the I.D. of the inlet and outlet with a stem motion of ~75 µm. The valve actuator is totally enclosed (with a filtered vent) to facilitate space flight level cleanliness. All threaded holes are vented to eliminate virtual leaks.

A cross section drawing of the MRC mini-valve is shown in Fig. 2. The valve components, including the removable seal at the seat, are all stainless steel except for the stem tip and the stem guide which are fabricated from a proprietary plastic composite. The unique low temperature sealing capability of the valve is related to the stem pressure and the geometry, materials selection, and surface treatments applied to the stem tip and valve seat.

In the sample handling system of the MISTE experiment, this valve will be actuated with a “hot-volume” reservoir. This reservoir will be filled with helium after cooldown and heated to ≤ 10 K to provide actuation pressure. This actuation approach simplifies the overall valve subsystem, since it eliminates a large and complicated room-temperature actuation-gas manifold system, and it also eliminates the actuation cycle limitation that would be caused by an limited supply of high-pressure gas for actuation. The only controls necessary to open the valve are a heater and a thermometer which are facilities readily available to the experiment.

Tests and Results

Before putting effort into the development of a pneumatic actuator system, preliminary tests were performed on a miniaturized tip and seat using a spring-loaded mechanical actuator driven by a shaft from room temperature. Once adequate force was applied, this system showed a leak rate of $< 10^{-9}$ scc/s at 4.2 K after 50 open/close cycles. Approximately 360 N of force on the valve tip was required for good performance.

Once obtained from MRC, the prototype valve shown in Fig. 1 was tested extensively at 4.2 K. In order to avoid contamination of the seat area by the gas used for testing, the test setup included a charcoal cold-trapped high purity helium supply system for the valve inlet. The helium gas was filtered with a 2 μm filter at room temperature just before entering the test cryostat, as well as at low temperature with a 0.5 μm VCR gasket filter [9] in a fitting directly adjacent to the valve inlet connection. The valve outlet line was not filtered to improve the response time of the leak detector, so any gas flow into the valve outlet was carefully avoided. This procedure was implemented to avoid carrying particulate contamination to the valve seat. The outlet plumbing from the valve to outside the test dewar as well as the inlet fitting between the final filter and the valve were all carefully cleaned of particulates before installation. A computer-controlled room temperature valve system allowed unattended actuation of the valve by alternately pumping and pressurized the actuation line. With this system we were able to perform over a hundred open/close cycles with 15 leak checks in about a week. All leak tests at 4.2 K were performed by first obtaining a low background reading with the leak detector while the valve inlet was pumped. Helium was then introduced to the inlet to a pressure of 7 to 10 kPa above atmospheric pressure. This pressure assured that the inlet side of the valve was filled with liquid helium. The leak rate due to this helium was then recorded after the valve temperature and the leak detector reading reached a stable value, which typically took up to an hour. This long time constant was presumably due to the adsorption of the initial helium onto the walls of the long, low temperature outlet line.

The valve was initially cooled closed and leak tested during two low-temperature runs. The valve was not disturbed during the room temperature thermal cycle between the runs. The leak rate versus actuation cycle results for the first two low temperature runs are shown in Fig. 3. The valve closing force was then increased by turning the adjusting screw shown in Fig. 2. This adjustment increased the differential pressure to open the valve at room temperature from about 520 kPa to 730 kPa. Opening pressures at low temperature were at most about 30 kPa different. Results of a subsequent low temperature test showed very similar leak versus cycle behavior, with only a slight decrease in magnitude of the leak rate.

The leak rate versus the actuation pressure after 6 cycles during the first cooldown is shown in Fig. 4. The curve gives an indication of how the leak rate varied as the closing force on the valve tip was reduced. Since increasing the force would correspond to going to negative pressure on the graph, the shallow slope of the curve near zero pressure is consistent with the small effect observed after the closing force was increased between the runs.

The valve behavior for all these tests is seen to be quite repeatable. During each cooldown the leak rate was approximately $N \times 3\times10^{-8}$ scc/s, where N is the number of open/close cycles since cooling to low temperature. The reason for the "resetting" of the leak rate back to a low value after a thermal cycle to room temperature is currently unknown.

In another test run the valve was cooled open, then closed and tested. A slight clog in the actuation line prevented a large number of cycles. For about 15 cycles the leak rate showed a similar upward trend as before, but with a starting leak rate after one cycle that was considerably higher, approximately 4×10^{-7} scc/s. These data are not shown in Fig. 3.

Conclusion

The current valve prototype marginally meets the stated leak rate requirement for the MISTE experiment, but improved performance would be desirable. Since the MISTE experiment uses ^{3}He, and thus has a rather less stringent requirement on the valve performance than superfluid ^{4}He experiments, it is perhaps the ideal project for the early development of a new small flight cryogenic valve. Further prototype tests are planned to determine the cause of the non-optimum, cycle dependent leak performance of the current version, and to hopefully decrease the leak rate by at least an order of magnitude. An earlier prototype suffered from a large leak rate due to the bottoming-out of the tip within the seat, which was made with a close tolerance to minimize dead volume. Possibly this problem was happening to a lesser extent in the current tests. We see no fundamental reason why this valve should not be able to reach a $< 10^{-9}$ scc/s leak rate up to ≈1000 cycles performance that has been demonstrated for this tip/seat combination in MRC's larger flight valve.

Acknowledgments

We would like to acknowledge technical assistance from Steve Elliott (JPL) and Craig Ward (MRC). The work at the Jet Propulsion Laboratory, California Institute of Technology, was carried out under contract with the National Aeronautics and Space Administration.

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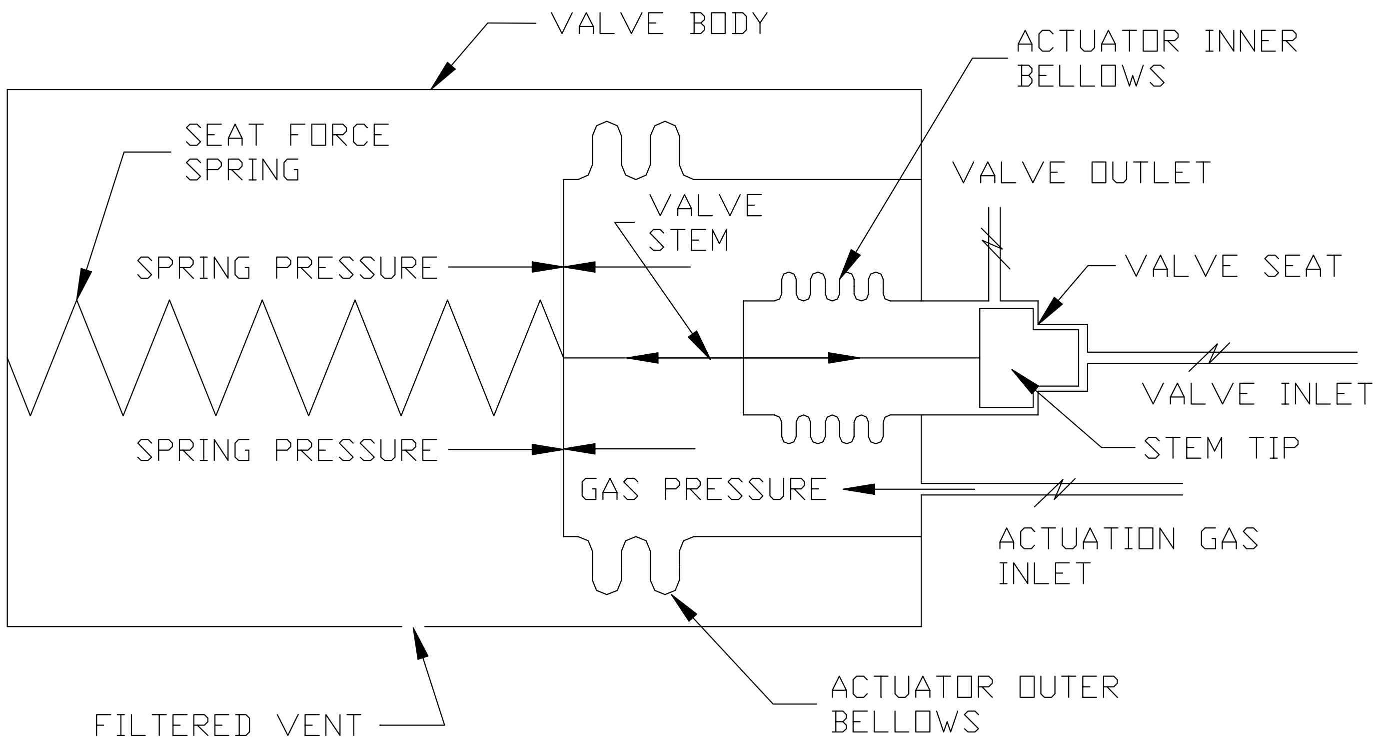
FIGURE CAPTIONS

Figure 1. Schematic diagram of the small cryogenic valve. Force from the spring keeps the valve normally closed. Actuation fluid pressure between the two bellows forces the valve open.

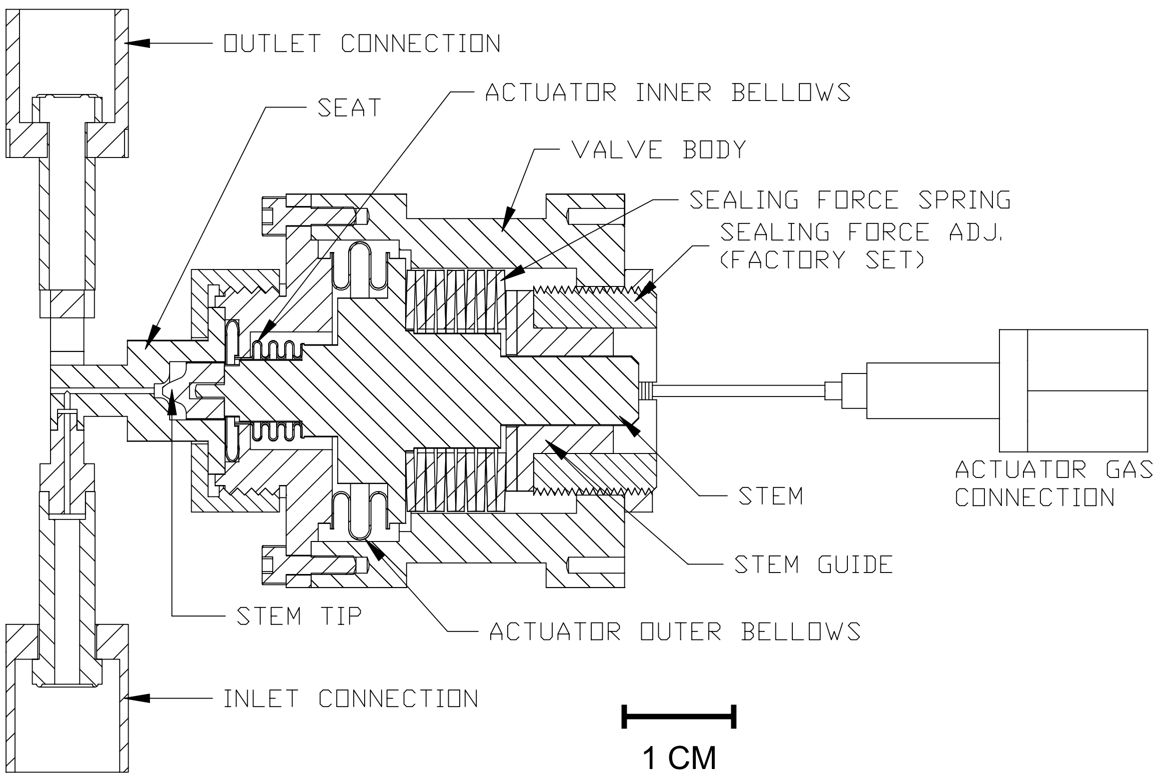
Figure 2. Cross section drawing of the valve.

Figure 3. Leak rate versus open/close cycles at 4.2 K. The points at 0.1 cycles on the logarithmic scale represent the leak before the valve was opened. The first two curves are consecutive cooldowns between which the valve was not modified. The last curve shows the leak rate after the valve closing force was increased by approximately 40%.

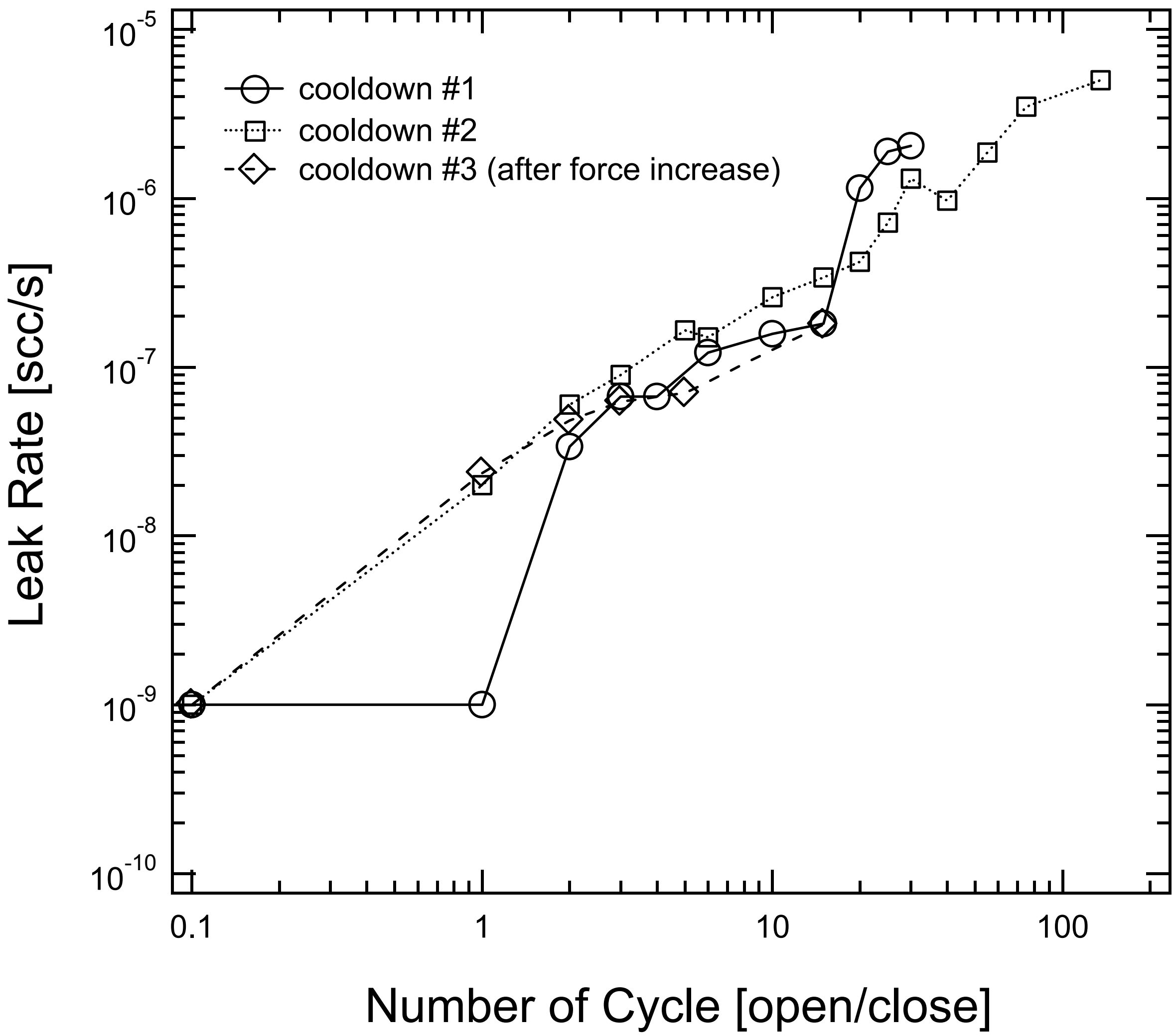
Figure 4. Leak rate versus actuation pressure, taken at 4.2 K after 6 low temperature open/close cycles. The valve was fully open at 520-525 kPa.



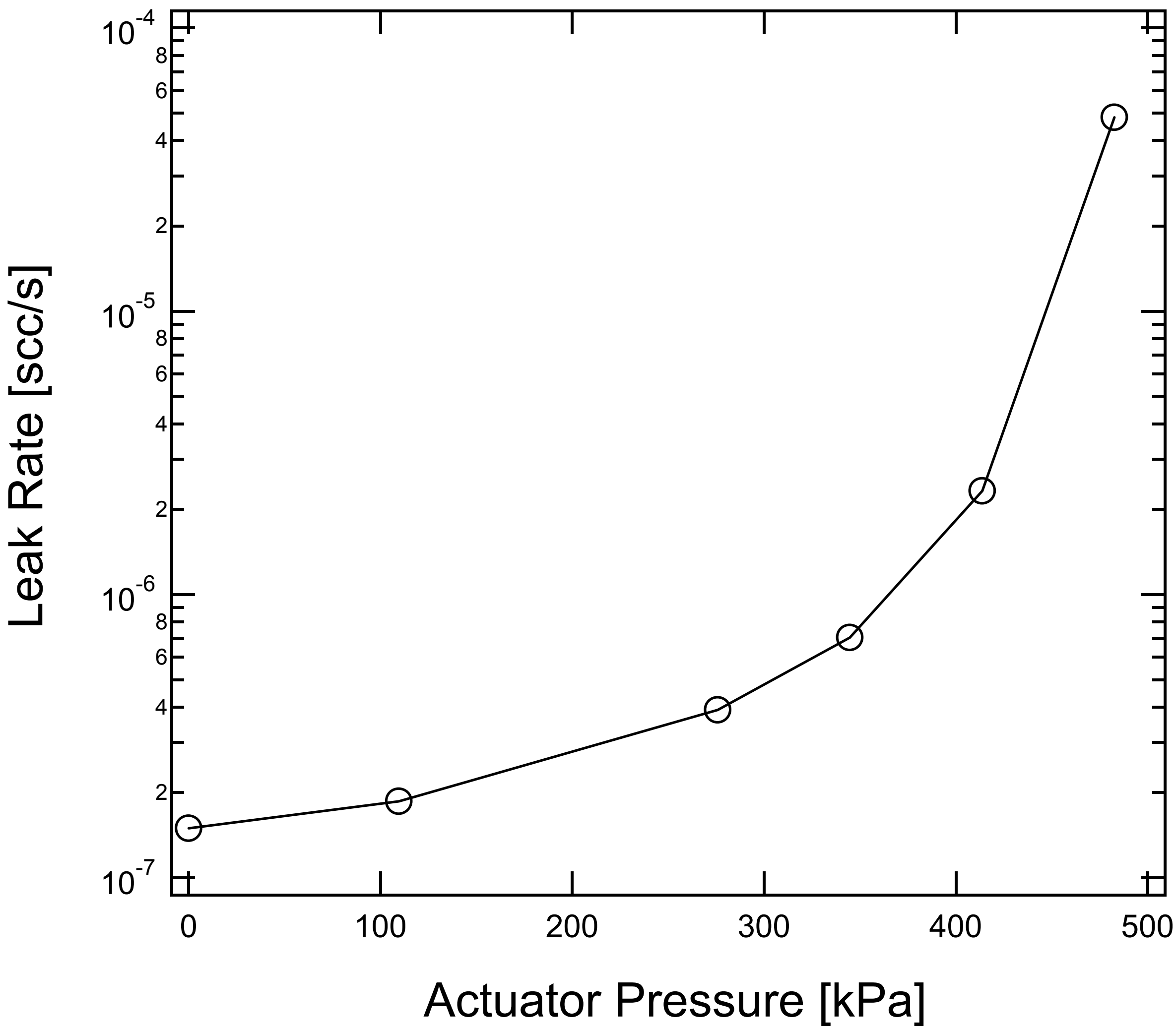
M. Weilert, FIGURE 1.



M. Weilert, FIGURE 2.



M. Weilert, FIGURE 3.



M. Weilert, FIGURE 4.